# HIGGS SEARCHES AT LEP2 WITH THE ALEPH DETECTOR

E. KNERINGER
*Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, AUSTRIA*
*ALEPH Collaboration*
*E-mail: Emmerich.Kneringer@uibk.ac.at*

Data collected with the ALEPH detector at centre-of-mass energies between 130 and 189 GeV are used to search for Higgs bosons of the standard model and its supersymmetric extensions. No evidence for a Higgs particle has been found in 256 pb$^{-1}$ of LEP2 data. Mass exclusion limits were set.

## 1 Introduction

A neutral Higgs boson is required to complete the particle spectrum of the standard model. Fits to electroweak data [1] from LEP, SLC and Tevatron indicate that if the Higgs particle exists it has most probably a mass around 100 GeV/$c^2$. The situation at LEP, which is summarized in Fig. 1 (left), shows that we are getting more and more sensitive to this mass range.

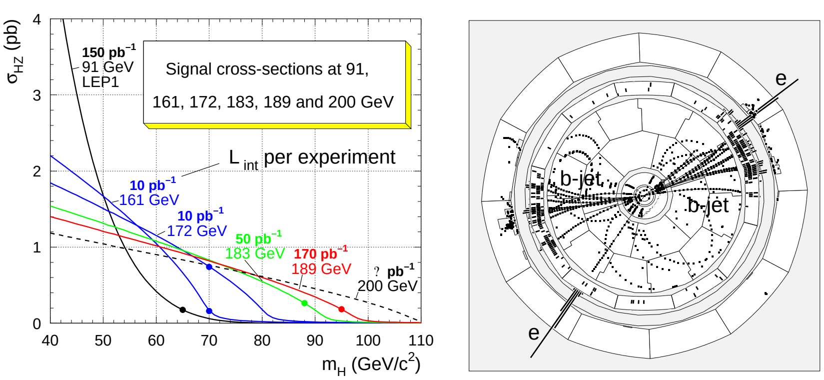


Figure 1: Left: cross section for the Higgs-strahlung process at the various LEP energies. For a given energy the point on the curve indicates the standard model Higgs boson mass exclusion limit obtained by a typical LEP experiment with the data taken at that energy. Right: Higgs boson candidate event in the $H\ell\ell$ channel (as seen by the ALEPH detector).

All mass exclusion limits given in this report are at 95% confidence level. To get an idea of the sensitivity of a specific analysis the expected mass exclusion limit [2] from gedanken experiments usually is also quoted. All the search analyses use cut-based selections and/or neural network methods. We make

extensive use of Monte Carlo simulations for the neural net training and the setting of the selection cuts. No details of the preliminary analyses are given, however, the references always point to the corresponding latest published analysis.

## 2 The Standard Model Higgs Boson

At LEP2, the dominant Higgs production mechanism is the so-called Higgs-strahlung process $e^+e^- \rightarrow Z^* \rightarrow HZ$. There are also minor contributions from processes where the Higgs boson is generated through the fusion of two electroweak gauge bosons. In the mass range accessible at LEP2, the Higgs boson decays in 92% of the cases into two quark jets (91% of which are $b\overline{b}$) and in about 8% of the cases into $\tau^+\tau^-$. Combining these numbers with the branching fractions of the Z boson we obtain the branching fractions of HZ into the following four characteristic event topologies:

- four jet channel: $q'\overline{q}'q\overline{q}$ (64.6%)
- missing energy channel: $H\nu\overline{\nu}$ (20.0%)
- lepton channel: $H\ell^+\ell^-$, $\ell = e$ or $\mu$ (6.7%)
- $\tau$–channel: either H or Z decays to $\tau^+\tau^-$ (8.7%)

Except for the lepton channel, a high b-quark content is required for the quark jets coming from Higgs boson decay. In all channels the invariant mass of the decay products of the Z must be compatible with $m_Z$. The results of the HZ analyses [3] applied to data taken with the ALEPH detector [4,5] at 189 GeV are summarized in Table 1.

Table 1: Signal efficiencies $\epsilon$, expected number of signal events $N_{95}^{exp}$ for $m_H = 95$ GeV/$c^2$, background expectation from standard model processes $N_{bkg}^{exp}$, background from ZZ events $N_{ZZ}^{exp}$ (dominant background source; irreducible) and number of observed events in 170 pb$^{-1}$ of ALEPH data taken at $\sqrt{s} = 189$ GeV for the HZ decay topologies.

| Selection | $\epsilon$ | $N_{95}^{exp}$ | $N_{bkg}^{exp}$ | $N_{ZZ}^{exp}$ | $N_{obs}$ |
|---|---|---|---|---|---|
| $b\overline{b}q\overline{q}$ | 39.3% | 7.7 | 18.5 | 10.1 | 20 |
| $b\overline{b}\nu\overline{\nu}$ | 24.3% | 1.6 | 3.7 | 3.1 | 7 |
| $b\overline{b}\ell^+\ell^-$ | 72.9% | 1.5 | 13.2 | 11.8 | 13 |
| $b\overline{b}\tau^+\tau^-$ | 20.1% | 0.2 | 0.8 | 0.6 | 2 |
| $\tau^+\tau^-q\overline{q}$ | 18.9% | 0.3 | 1.8 | 1.2 | 0 |
| total | | 11.3 | 38.0 | 26.8 | 42 |

The analyses for the four individual channels are optimized in such a way that the combination of these analyses gives the best global HZ searches analysis. The definition used here for 'best analysis' is: the analysis which gives the highest expected Higgs mass exclusion limit under the hypothesis that there is no signal [2].

No signal is observed in 250 $\mathrm{pb}^{-1}$ of data (*cf.* $m_{\mathrm{h}}$ distribution in Fig. 2) which allows to exclude a standard model Higgs boson with a mass less than 90.4 GeV/$c^2$, as shown in Fig. 2 (right). The expected limit is 93.4 GeV/$c^2$.

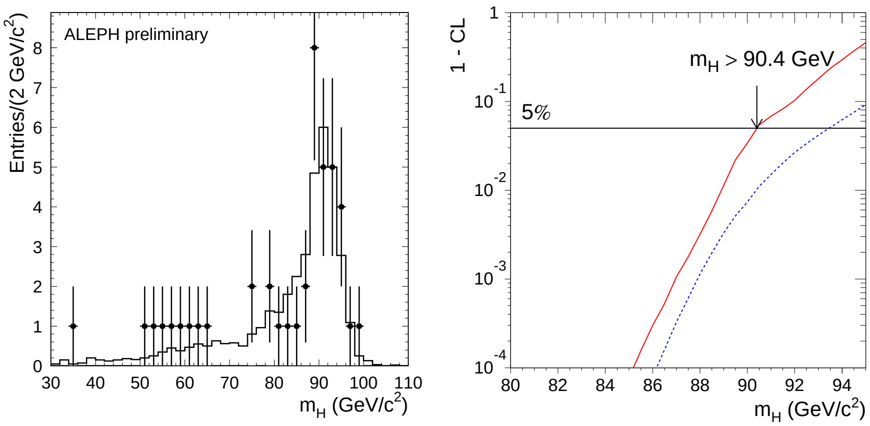


Figure 2: Left: distribution of $m_{\mathrm{H}}$ of the selected events (points) and the expectation from the standard model background processes (histogram) in HZ searches at $\sqrt{s} = 189$ GeV. Right: observed (full line) and expected (dashed line) combined confidence levels for the standard model Higgs search.

## 3 Neutral Higgs Bosons of the MSSM

The particle spectrum of the Higgs sector of the minimal supersymmetric extension of the standard model (MSSM) consists of five physical states, two CP-even neutral bosons h and H (with mixing angle $\alpha$ and masses $m_{\mathrm{h}} < m_{\mathrm{H}}$), one CP-odd neutral boson A and two charged bosons $\mathrm{H}^{\pm}$. At tree level, the Higgs sector can be parameterized by two independent parameters, *e.g.* $m_{\mathrm{h}}$ and $\tan\beta = v_2/v_1$, the ratio of the vacuum expectation values of the two Higgs doublets. Only the h and A bosons are within the reach of LEP2. They are expected to be produced in Z decays via the Higgs-strahlung process $\mathrm{Z}^* \rightarrow \mathrm{hZ}$, with a cross section proportional to $\sin^2(\beta - \alpha)$, and via the associated pair production $\mathrm{Z}^* \rightarrow \mathrm{hA}$, with a cross section proportional to $\cos^2(\beta - \alpha)$.

These two processes are complementary, in the sense that if one cross section is maximal the other is minimal and vice versa. Thus both processes must be searched for. For the first process, the results from the hZ searches (Sec. 2) can be used. The second process is searched for in the following two decay channels:

- $hA \to b\bar{b}b\bar{b}$ (85%)
- $hA \to b\bar{b}\tau^+\tau^-$, $\tau^+\tau^- b\bar{b}$ (15%)

The performance of the two analyses [6] is reported in Table 2.

Table 2: Performance of the hA analyses at $\sqrt{s} = 189$ GeV: signal efficiencies, expected number of signal events for $m_h = m_A = 85$ GeV/$c^2$, background expectation and number of observed events.

| Selection | $\epsilon$ | $N_{85}^{exp}$ | $N_{bkg}^{exp}$ | $N_{obs}$ |
|---|---|---|---|---|
| $b\bar{b}b\bar{b}$ | 58.3% | 3.4 | 9.0 | 13 |
| $b\bar{b}\tau^+\tau^-$ | 24.0% | 0.2 | 0.6 | 0 |

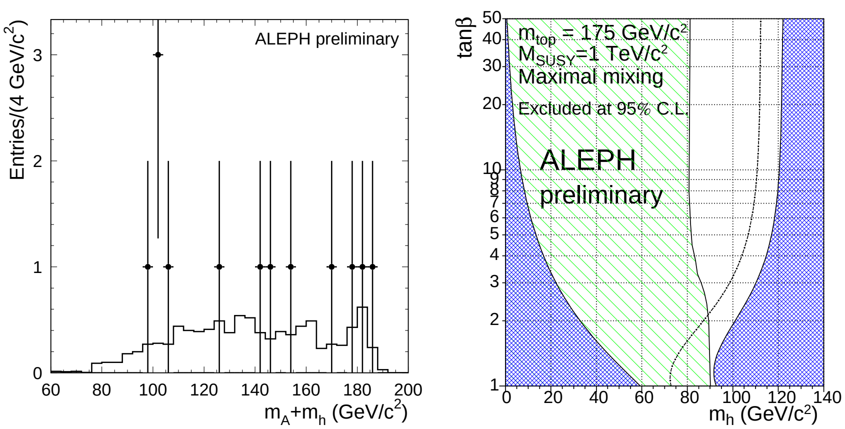


Figure 3: Left: distribution of $m_A + m_h$ of the selected events (points) and the expectation from the standard model background processes (histogram) in hA searches at $\sqrt{s} = 189$ GeV. Right: experimentally excluded region in the $[m_h, \tan\beta]$ plane (after combination with the hZ searches). The dark area represents the theoretically forbidden region for the case of 'maximal stop mixing' (dashed-dotted curve for the 'no stop mixing' case).

No signal is observed in the data, as can be seen in Fig. 3 (left). This allows to set an upper limit on the cross section for hA production as a function of

$m_{\rm h}$, which implies an upper limit on $\cos^2(\beta-\alpha)$ as a function of $m_{\rm h}$. On the other hand, the hZ searches interpreted in this way result in an upper limit on $\sin^2(\beta-\alpha)$ as a function of $m_{\rm h}$. Combining the hZ and hA searches in an optimal way [2] leads to an excluded region in the two-dimensional parameter space $[m_{\rm h}, \sin^2(\beta-\alpha)]$, which usually is translated to the $[m_{\rm h}, \tan\beta]$ plane, as shown in Fig. 3 (right). For $\tan\beta \geq 1$ we find that ALEPH data up to centre-of-mass energies of 189 GeV exclude the h and A Higgs bosons of the MSSM with masses less than 80.8 and 81.2 GeV/$c^2$, respectively, *i.e.* the neutral Higgs bosons must be heavier than the W boson if $\tan\beta \geq 1$.

## 4 Charged Higgs Bosons

In the MSSM charged Higgs bosons are heavier than W bosons. This restriction does not hold for general two doublet models, which are very attractive theoretically because of the absence of flavor changing neutral currents and the relation $m_{\rm W} = m_{\rm Z}\cos\theta_W$ holding at tree level. The $\rm H^\pm$ has the same decay modes as the $\rm W^\pm$, but since its coupling is proportional to the charged fermion masses, it dominantly decays into the heaviest energetically allowed fermion pair of the quark and lepton families. Whether $\rm H^\pm$ decay preferentially into quarks or leptons depends on other parameters of the model. Therefore, the search for pair-produced $\rm H^+H^-$ is performed in the following three channels:

- leptonic channel: $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$
- mixed channel: $\rm c\bar{s}\tau^-\bar{\nu}_\tau$
- hadronic or four jet channel: $\rm c\bar{s}s\bar{c}$

The performance of these analyses [7] is summarized in Table 3.

Table 3: Efficiencies $\epsilon$, number of standard model background events expected $N_{bkg}^{exp}$ and number of observed candidates $N_{obs}$ for the three charged Higgs boson analyses at a centre-of-mass energy of 189 GeV, as functions of the charged Higgs mass. For the four jet channel, numbers are quoted within a $\pm 3$ GeV/$c^2$ window around the assumed Higgs boson mass.

| $m_{\rm H^\pm}$ | $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$ | | | $\rm c\bar{s}\tau^-\bar{\nu}_\tau$ | | | $\rm c\bar{s}s\bar{c}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| (GeV/$c^2$) | $\epsilon$ (%) | $N_{bkg}^{exp}$ | $N_{obs}$ | $\epsilon$ (%) | $N_{bkg}^{exp}$ | $N_{obs}$ | $\epsilon$ (%) | $N_{bkg}^{exp}$ | $N_{obs}$ |
| 50 | 33.5 | 15.5 | 20 | 35.6 | 9.4 | 11 | 40.1 | 15.1 | 18 |
| 55 | 35.2 | 15.5 | 20 | 37.2 | 9.4 | 11 | 38.4 | 22.8 | 23 |
| 60 | 38.2 | 15.5 | 20 | 37.4 | 9.4 | 11 | 37.6 | 28.0 | 19 |
| 65 | 35.2 | 15.5 | 20 | 34.8 | 9.4 | 11 | 37.2 | 30.6 | 28 |
| 70 | 39.9 | 15.5 | 20 | 28.1 | 9.4 | 11 | 36.4 | 32.7 | 35 |
| 75 | 40.8 | 15.5 | 20 | 19.1 | 9.4 | 11 | 34.6 | 55.1 | 40 |

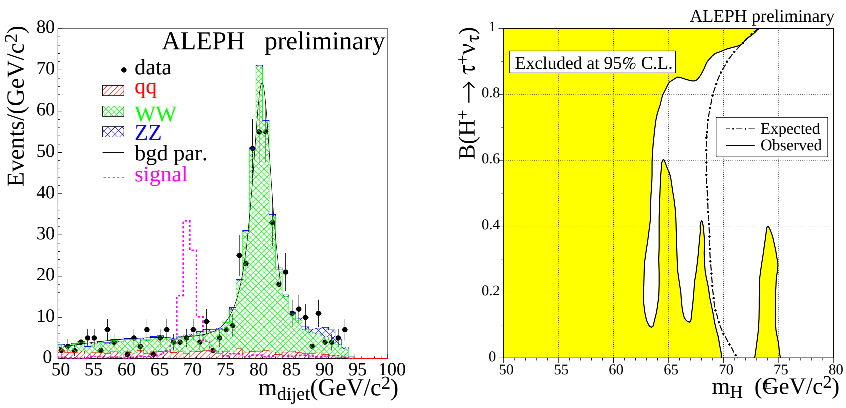


Figure 4: Left: distribution of the dijet mass distribution as obtained after applying all cuts of the c$\bar{s}\bar{s}$c selection; shown are 189 GeV data (dots), background Monte Carlo (histogram) and the polynomial parameterization of the background (full line). Also shown is the Monte Carlo expectation for a signal with $m_{\mathrm{H}^\pm} = 70$ GeV/$c^2$ (dashed line) with arbitrary normalization. Right: limit on the mass of charged Higgs bosons as a function of $\mathcal{B}(\mathrm{H}^+ \to \tau^+\nu_\tau)$. Shown are the expected (dash-dotted) and observed (full) exclusion curves for the combination of the three charged Higgs boson analyses. The shaded area is excluded at 95% C.L.

The search for charged Higgs bosons in the three final states $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$, c$\bar{s}\tau^-\bar{\nu}_\tau$ and c$\bar{s}\bar{s}$c has been performed using 175 pb$^{-1}$ of ALEPH data collected at $\sqrt{s} = 189$ GeV. No evidence of Higgs boson production was found (Fig. 4 left) and mass limits were set as a function of the branching ratio $\mathcal{B}(\mathrm{H}^+ \to \tau^+\nu_\tau)$. The result of the combination of the three analyses is displayed in Fig. 4 (right) where the curves corresponding to expected and observed confidence levels of 95% exclusion are drawn. As can be seen from this figure, charged Higgs bosons with masses below 62.5 GeV/$c^2$ are excluded at 95% C.L. independently of $\mathcal{B}(\mathrm{H}^+ \to \tau^+\nu_\tau)$, where the expected mass exclusion limit is 68.5 GeV/$c^2$.

## 5 Invisible Higgs Boson Decays

Many extensions of the standard model allow for the Higgs boson to decay invisibly, *e.g.* into a pair of lightest neutralinos when the neutralino $\chi$ is light enough. Since the Higgs boson is produced through the Higgs-strahlung process hZ, this leads to the following two event topologies:

- a pair of acoplanar leptons, when $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ or $\mathrm{Z} \to \mu^+\mu^-$

- a pair of acoplanar jets, when the Z decays hadronically

where the acoplanarity is defined as the azimuthal angle between the two lepton or jet directions. Two analyses [8] are designed for the two channels. When they are applied to ALEPH data taken at $\sqrt{s} = 189$ GeV, 33 candidates are found, in agreement with 33.6 events expected from all background processes (*cf.* Table 4). The distributions of the reconstructed Higgs boson masses are shown in Fig. 5 (left).

Table 4: Performance of the acoplanar lepton and acoplanar jet pair analyses.

| Selection | $N_{bkg}^{exp}$ | $N_{obs}$ |
|---|---|---|
| $\mathrm{h}\ell^+\ell^-$ | 4.3 | 5 |
| $\mathrm{hq\bar{q}}$ | 29.3 | 28 |

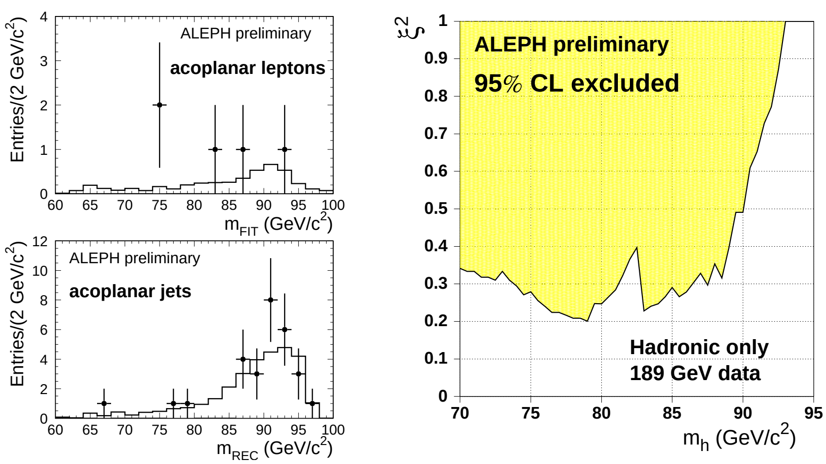


Figure 5: Left: distribution of the reconstructed Higgs boson mass of the selected events compared to the Monte Carlo expectation, for the acoplanar lepton and jet pair searches. Right: region in the $[m_{\mathrm{h}},\ \xi^2]$ plane excluded at 95% C.L. using only the hadronic channel at 189 GeV.

Quite generally, the production cross section for invisible Higgs boson decay can be parameterized as $\xi^2 \cdot \sigma_{\mathrm{SM}}(\mathrm{e^+e^-} \to \mathrm{hZ})$, where $\xi^2$ is a model dependent factor ranging from 0 to 1. One way of presenting the result of the negative searches is to calculate the 95% C.L. level upper limit on the production cross section of the invisibly decaying Higgs boson in units of $\sigma_{\mathrm{SM}}(\mathrm{e^+e^-} \to \mathrm{hZ})$ as a function of $m_{\mathrm{h}}$, which is shown in Fig. 5 (right).

## 6 Summary

In this report, an overview has been given of the present status of Higgs boson searches with the ALEPH detector. The results are mainly based on the analysis of data taken at 189 GeV centre-of-mass energy. When the data taken at lower energies are included in the analyses the 95% confidence level exclusion limits improve slightly.

For the standard model Higgs boson we find $m_{\mathrm{H}} > 90.4$ GeV/$c^2$ at 95% C.L. using 250 pb$^{-1}$ of data taken at $\sqrt{s} = 161$, 172, 183 and 189 GeV. This means that a Higgs boson with a mass equal to the Z mass just cannot be excluded at 95% C.L. with ALEPH data taken up to the year 1998.

Including all lower energy data, for the neutral Higgs bosons of the MSSM we obtain the limits $m_{\mathrm{h}} > 80.8$ GeV/$c^2$ and $m_{\mathrm{A}} > 81.2$ GeV/$c^2$ (valid for all values of $\tan\beta \geq 1$).

From the analysis of 175 pb$^{-1}$ of ALEPH data collected in 1998, the charged Higgs bosons of general two doublet models are excluded below 62.5 GeV/$c^2$ independent of their decay mode.

Finally, using the same data, invisibly decaying Higgs bosons are searched for. For a production cross section equal to that of the standard model Higgs boson, *i.e.* $\xi^2 = 1$, masses below 92.8 GeV/$c^2$ are excluded.


### Acknowledgments

I would like to thank all my colleagues from the ALEPH Higgs Task Force for the continuous effort to produce all these results.


### References


1. LEP Electroweak Working Group, CERN-EP/99-15.
2. P. Janot and F. Le Diberder, *Nucl. Instrum. Methods* A **411**, 449 (1998).
3. ALEPH Collaboration, *Phys. Lett.* B **440**, 403 (1998).
4. ALEPH Collaboration, *Nucl. Instrum. Methods* A **294**, 121 (1990).
5. ALEPH Collaboration, *Nucl. Instrum. Methods* A **360**, 481 (1995).
6. ALEPH Collaboration, *Phys. Lett.* B **440**, 419 (1998).
7. ALEPH Collaboration, *Phys. Lett.* B **450**, 467 (1999).
8. ALEPH Collaboration, *Phys. Lett.* B **450**, 301 (1999).